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THE $z = 5.8$ QUASAR SDSSp J1044−0125: A PEEK AT QUASAR EVOLUTION?

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ABSTRACT

The newly discovered $z = 5.8$ quasar SDSSp J104433.04−012502.2 was recently detected in X-rays and found to be extremely X-ray weak. Here we present the hardness ratio analysis of the *XMM-Newton* observation. We consider various models to explain the detection in the soft X-ray band and nondetection in the hard band, together with its X-ray weakness. We show that the source may have a steep power-law slope, with an absorber partially covering the continuum. This may be X-ray evidence to support the recent argument of Mathur that narrow-line Seyfert 1 galaxies, which show steep power-law slopes, might be the low-redshift, low-luminosity analogs of the high-redshift quasars. Heavily shrouded and steep X-ray spectrum quasars may indeed represent the early stages of quasar evolution, and SDSSp J104433.04−012502.2 is possibly giving us a first glimpse of the physical evolution of quasar properties.

Key words: galaxies: active — galaxies: evolution — galaxies: nuclei — quasars: general — quasars: individual (SDSSp J104433.04−012502.2) — X-rays

1. INTRODUCTION

The discovery of a quasar at redshift $z = 5.8$ (Fan et al. 2000) was remarkable as it showed that luminous quasars with massive black holes had formed when the universe was less than 1 Gyr old. The quasar SDSSp J104433.04−012502.2 (hereafter SDSS 1044−0125) was discovered as part of the Sloan Digital Sky Survey imaging multicolor observations. The follow-up spectrum with Keck revealed a rich spectrum of a quasar at $z = 5.8$ with strong Lyα forest. Brandt et al. (2001, hereafter Paper I) then observed the quasar in X-rays with *XMM-Newton*. The quasar was clearly detected but found to be unusually X-ray weak. The source was too faint to do meaningful spectral analysis.

To extract spectral information from only a few tens of counts, X-ray astronomers have traditionally used a hardness ratio analysis (Maccacaro et al. 1988). The observed photons are divided into two energy bands, soft (S) and hard (H), for low energy and high energy, respectively. The hardness ratio HR $= H-S/H+S$ then gives a measure of the shape of the X-ray spectrum. A more sophisticated version of the hardness ratio method has been used by various authors to extract valuable information on high-redshift quasars: Bechtold et al. (1994) found that the radio-quiet high-redshift quasars either have steeper power-law slopes and large absorbing columns or no absorption and power-law slopes similar to their lower redshift cousins. Based on a detection with *Einstein*, Mathur & Elvis (1995) concluded that the high-redshift radio-loud quasar GB 1508+5714 either has an unusually hard power-law slope or is highly absorbed. Later observations have confirmed the unusually hard slopes of high-redshift radio-loud quasars (e.g., Moran & Helfand 1997; Reeves et al. 2001). The hardness ratio analysis thus provides us with a powerful tool to extract spectral information when the total observed counts are too small to perform detailed spectral analysis.

In this paper we perform the hardness ratio analysis on the highest redshift quasar, SDSS 1044−0125, to expand on the work already reported in Paper I.

2. *XMM* OBSERVATIONS OF SDSS 1044−0125

SDSS 1044−0125 was detected with *XMM* EPIC-pn. The total counts observed in the 0.5–2.0 keV band were 32 ± 9. This corresponds to the rest-frame energy range 3.4–13.6 keV (see Paper I for the details of observation). Based on this observed count rate, SDSS 1044−0125 is unusually X-ray weak; it has about a factor of 10 smaller X-ray flux for its optical observed flux relative to other luminous optically selected quasars (Paper I). These observations imply that either (1) the object is intrinsically X-ray weak, and so is a very unusual quasar, or (2) it is a normal quasar that is heavily absorbed, with a column density $N_{\rm H} \gtrsim 10^{24}$ cm^{-2}, as seen in some broad absorption line quasars (BALQSOs). Brandt et al. have discussed both of these possibilities, though the latter was their preferred interpretation.

Note also that SDSS 1044−0125 was not detected in the 2.0–7.0 keV band (rest-frame energy range 13.6–47.6 keV). Since hard X-rays are less affected by photoelectric absorption, the nondetection in the hard band was rather surprising if heavy absorption was indeed the cause of X-ray weakness of the object.[1] In most BALQSOs, for example, X-ray detections are preferentially in the hard band (Mathur et al. 2000 and references therein). Another point to note is that the low spectral resolution X-ray observations cannot determine the redshift of the absorber. Absorption at lower redshift with smaller column density may mimic the absorption at high redshift with larger column density of gas. Given that SDSS 1044−0125 is at very high redshift and that there is a lot of absorption along the line of sight, including that due to a Lyman limit system and a Mg II system (Fan et al. 2000), the X-ray absorption may take place in the intervening systems. To study these different possibilities and to extract further spectral information, we perform a hardness ratio analysis of SDSS 1044−0125.

[1] We note that Brandt et al. have mentioned that perhaps partial covering of the X-ray continuum source may explain the photons detected at $\lesssim 8$ keV.

2.1. *Hardness Ratio Analysis*

For SDSS 1044−0125, the total counts detected in the soft band are 31.7 ± 8.5, and the upper limit in the hard band is 12.3 counts (95% confidence; Paper I). This results in the hardness ratio HR < -0.44. The maximum HR (assuming minimum soft counts, $-1\,\sigma$) is -0.31. In Figure 1 we have plotted the expected HR as a function of the X-ray power-law slope, Γ ($1 + \alpha$ for $f_\nu \propto \nu^{-\alpha}$), for a range of absorbing column densities. We have used the 0.5–2.0 keV range for the soft band and the 2.0–7.0 keV range for the hard band as in Brandt et al. All the HR calculations were performed using the Portable, Interactive, Multi-Mission Simulator (PIMMS, Version 3.0; Mukai 2000), and XSPEC (Arnaud 1996) was used to define the spectral models (see Paper I for the appropriateness of using PIMMS). The lowest curve corresponds to Galactic column density of 4.6×10^{20} cm^{-2} toward SDSS 1044−0125, the next curve corresponds to column density 10 times Galactic, and the top one corresponds to column density of 1.7×10^{22} cm^{-2}. These are all column densities at $z = 0.0$. The highest column density plotted in Figure 1 is that required for the suppression of the soft flux by a factor of 10 and would correspond to $\gtrsim 10^{24}$ cm^{-2} at $z = 5.8$. If the quasar is not intrinsically X-ray faint, then this much absorption is required to suppress the total flux to the observed value. What is immediately apparent from Figure 1 is that the required excess absorption is inconsistent with the observed hardness ratio *for any reasonable value of* Γ.

What, then, is the possible spectral shape of SDSS 1044−0125 consistent with the observed hardness ratio? A simple power law with just Galactic absorption and slope in the normal range $\Gamma \approx 2$ is consistent with observations (also noted by Brandt et al.). This, however, makes the quasar unusually X-ray weak. There are a few ways to make the heavy absorption scenario consistent with the observed hardness ratio: (1) a high-energy cutoff in the observed band (this will bring down the number of hard X-ray photons), (2) a completely Compton thick X-ray absorber suppressing both soft and hard X-ray flux, but partially covering the continuum source and leaking some soft photons, and (3) a partially covering absorber and a steep X-ray spectrum. Below we consider each of these possibilities in turn. One immediate conclusion of the above exercise is that the absorber must be close to the continuum source for partial covering to work. So it is highly unlikely that the X-ray absorption is caused by the intervening matter.

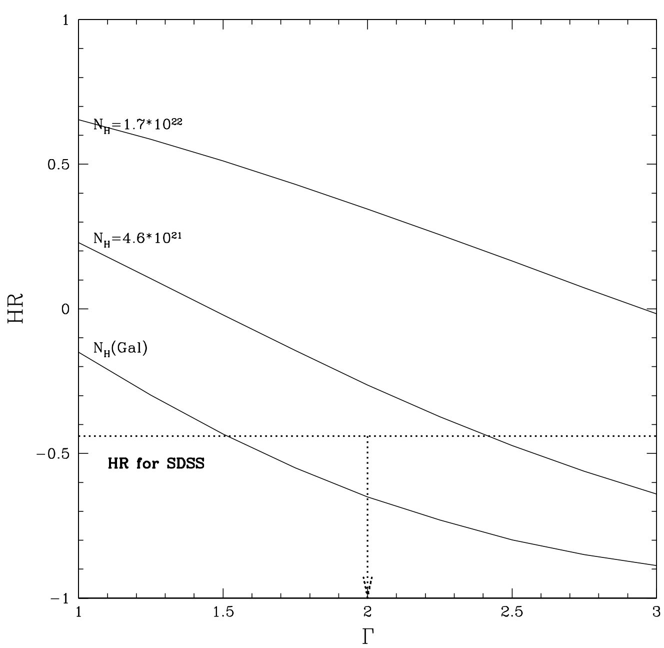

FIG. 1.—Calculated hardness ratio plotted as a function of X-ray power-law photon index for a range of absorbing column densities at $z = 0$. The horizontal line represents the observed upper limit for SDSS 1044−0125. The top curve corresponds to the column density required to suppress the soft X-ray flux by a factor of 10. This model is inconsistent with observed HR for any reasonable value Γ. The observed HR is consistent with only Galactic absorption, but that will make the quasar extremely X-ray weak.

2.1.1. *High-Energy Cutoff*

High-energy cutoffs to the power-law spectra are expected from the thermal Comptonization models and are required to explain the cosmic hard X-ray background. There is no universal value for a cutoff energy, but generally it is assumed to be $\approx$270 keV (e.g., Matt 1998). This is too high to have any effect on the observed hard band (rest-frame energy range 13.6–47.6 keV). To our knowledge, the lowest value of high-energy cutoff observed so far is that for the highly absorbed maser source ESO 103-G35 (Wilkes et al. 2001). It may have a cutoff energy as low as 30 ± 10 keV. We calculated hardness ratios for cutoff energies of 20, 30, and 40 keV for $\Gamma = 2.0$ and the *e*-folding energy of 20 keV. The resulting HR values are $+0.22$, $+0.31$, and $+0.34$, respectively. There values are well above the observed HR for SDSS 1044−0125. We then repeated the above experiment for steeper power-law slopes. The results indicate that if the high-energy cutoff model is to account for the observed HR, then the cutoff energy has to be smaller than 20 keV *and* Γ has to be steeper than 3. This, again, is extremely unusual.

2.1.2. *Compton Thick Absorber with Partial Covering*

If an absorber near the source is completely Compton thick (say, $N_{\rm H} = 10^{25}$ cm^{-2}), then the continuum is completely suppressed, even in the high-energy band. This happens because the high-energy photons are down-scattered to lower energy, at which they are effectively absorbed by photoelectric absorption (Matt 1998). If such an absorber does not cover the source completely, with 10% of the continuum leaking through, then the observed X-ray flux is naturally 1/10 of the intrinsic flux. This can happen either as a result of the geometry of the absorber or as a result of scattering toward our line of sight. Such a scenario with a normal power-law slope of $\Gamma = 2$ then explains the observations, including the hardness ratio (§ 2.1). We have verified with explicit simulations that indeed for a model with $\Gamma = 2$ and for an absorber with 90% covering, a column density of as much as $N_{\rm H} = 10^{25}$ cm^{-2} is required to suppress the total flux by a factor of 10.

Such a model, however, has other consequences. The absorber in this case is not only thick to Compton scattering, it is also thick to Thomson scattering. Thomson scattering is achromatic (up to $m_e c^2$) and would result in attenuation at all wavelengths, including optical and UV (unless the absorber covers the whole sky as seen by the source). For the column density quoted above, the Thomson optical depth, $\tau_{\rm Th} = 6.65$, with attenuation factor of

773. Thus the source would be heavily attenuated, not only in the X-rays, but also in UV. This is not unusual. Broad absorption line quasars, which show strong X-ray absorption, also suffer from attenuation in the optical–UV by an amount appropriate for their observed column densities (e.g., Mathur et al. 2000 and references therein). In NGC 1068, a classic example of Seyfert 2 galaxies, in which the X-ray absorber is believed to be Compton thick (e.g., Guainazzi, Matt, & Fiore 2000), the optical and UV continuum is also completely obscured.

On the other hand, SDSS 1044−0125 is luminous in optical (rest-frame UV). Even at the observed flux levels, the luminosity of the object requires a black hole (BH) of $3 \times 10^9\ M_\odot$ accreting at the Eddington rate (Fan et al. 2000). If the intrinsic luminosity of the source were significantly higher, then it would push the required BH mass to significantly higher values. In the framework of hierarchical models of structure formation, Haiman & Loeb (2001) have calculated the maximum allowed BH mass as a function of redshift that could be found in a given survey. At $z = 5.8$ and BH mass of $3 \times 10^9\ M_\odot$, SDSS 1044−0125 is already at a model limit (see their Fig. 3). While not impossible, an increase of orders of magnitude in the implied BH mass would be stretching the limits. Moreover, if the observed optical flux of SDSS 1044−0125 is also significantly attenuated, then it does not solve the problem of X-ray weakness of the object.

One way out of this problem is to place the Compton thick X-ray absorber outside the X-ray–emitting region but inside the region emitting UV. This would be extremely difficult given that the X-ray–UV emission arises from a few to a few tens of Schwarzschild radii away from the nuclear black hole, and especially if UV photons provide the seed population for Compton up-scattering to produce X-rays (e.g., Nandra 2001).

2.1.3. *Steep X-Ray Spectrum and a Partially Covering Absorber*

To alleviate the above problem, we considered a model in which the X-ray continuum of the source has a steep spectrum and, again, a partially covering absorber along our line of sight. A steeper continuum would reduce the hard X-ray flux for a given normalization, while the absorber would suppress the soft X-ray flux. The required column density of the absorber then may not be excessive. Such a model is physically motivated. SDSS 1044−0125 seems to be a broad absorption line quasar (Maiolino et al. 2001). There is some evidence that the X-ray power-law slopes of BALQSOs may be steep (Mathur et al. 2001; although see Green et al. 2001).

So we constructed a model with $\Gamma = 2.5$ and the covering factor of the absorber 90%. We then varied the column density of the absorber from $N_H = 10^{22}$ to 10^{25} cm^{-2}. In each case we noted the factor by which the intrinsic flux was suppressed and calculated the hardness ratio. A factor of 10 smaller flux (compared with an unobscured source with $\Gamma = 2$) is obtained for $N_H \sim 7 \times 10^{23}$ cm^{-2}. The hardness ratio in this case is between −0.47 and −0.58, consistent with the observed value. Thus such a model satisfies constraints from both flux and HR. The implied Thomson opacity in this case is ≈ 0.5, resulting in no significant attenuation in optical–UV. The derived column density is also consistent with that observed in other BALQSOs (Mathur et al. 2000, 2001; Green et al. 2001; Gallagher et al. 2001).

3. DISCUSSION

We are aware that only 33 counts were detected in the *XMM* observation of SDSS 1044−0125. Trying to extract much more information from this observation might seem like overinterpreting the data. However, the hardness ratio analysis has been used in situations like this. This paper not only shows the power of this technique, but it also draws important conclusions from its use.

We show that the X-ray properties of this $z = 5.8$ quasar are unlikely to be exactly like its low-redshift cousins. It is either extremely X-ray weak (Paper I) or it has a steep power-law slope. Since we are looking at an object at the time when the structures in the universe were very young, it may be even more of a surprise if it looked exactly like nearby quasars. Quasars must evolve, and the evolution of quasar luminosity function has been observed. However, we still do not know *how* quasars evolve. With the observation of SDSS 1044−0125 we might be getting a first look at the evolution of quasar spectra with time. Heavily shrouded and steep hard X-ray spectrum quasars may represent an early evolutionary stage (Fabian 1999; Mathur 2000). Given the extremely large luminosity of the object (Fan et al. 2000), it is most likely accreting at an Eddington, or even super-Eddington rate. The narrow-line Seyfert 1 galaxies (NLS1s), nearby active galactic nuclei believed to be accreting at close to the Eddington rate, also have steep hard X-ray spectra (Brandt, Mathur, & Elvis 1997). Mathur (2000) has argued that the NLS1 galaxies might be low-redshift, low-luminosity analogs of the high-redshift quasars. Here we might be seeing X-ray evidence in support of that argument. But can accretion onto a $10^9\ M_\odot$ black hole produce X-rays with such steep power-law slopes? It would challenge current accretion disk theories. Clearly, good X-ray spectra of radio-quiet high-redshift quasars are needed to confirm this hypothesis.

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